Frost Effects in Soil-Steel Bridges

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The durability of soil-steel structures may be governed by the frost effects in the soil backfill and under the invert. The mechanics of frost action and its harmful effects on conduits, especially pipe arches carrying water, are discussed. The present OHBD code and AASHTO specifications need to be revised to avoid placing frost-susceptible soil within the depth of frost penetration through the backfill, and the bedding should be provided with enough depth to avoid frost upheaval in the case of frost-susceptible native soil. Water seepage should also be prevented through the bedding to avoid infiltration of fine particles, which could change the character of clean granular soil under the invert into frost-susceptible soil.

The durability of soil-steel structures may be governed by frost effects because of the forces induced on the conduit walls and their surrounding soil or because of the change in bearing capacity or the mechanical properties of the soil through the freeze-thaw cycles.

Frost effects are usually considered to be important criteria in the design of roads. They should also be eliminated or taken into consideration in the design of soil-steel bridges. This fact is emphasized with the recent reports of distress conditions for a number of soil-steel bridges (*1*,*2*). The authors have also observed upheaval of the invert and bolt tearing at the haunches in a few pipe arches in Ontario (*3*). These distresses are believed to be caused mainly by frost effects.

This paper examines the possible effects of frost action on soil-steel structures. It also examines the present OHBD code and the AASHTO specifications from the point of view of frost action and suggests possible code changes and backfill material modification to improve the durability of the structures.

FREEZING AND THAWING EFFECTS

Freezing

When a freezing front advances through soil, water may either be expelled or attracted to the freezing front depending on the soil type, stress level, and rate of freezing (*4*). The geotechnical implications of this phenomenon are as follows.

1. If water is expelled by an advancing freezing front, the soil is classified as frost nonsusceptible. Herein, positive excess pore pressure can be generated in the case of blocked drainage, leading to a decrease in the effective stress and accordingly to a decrease in the stiffness of the soil.

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2. If water is attracted to the freezing front, the soil is classified as frost susceptible. This phenomenon is also known as ice segregation, in which water is drawn from unfrozen soil to the freezing front, where it attaches to form layers of ice, forcing soil particles apart and causing the soil surface to heave. Without physical restraint there is no apparent limit to the amount of heaving that may occur. Where restraint is present in the form of a building load, heaving pressures may or may not overcome the restraint.

Mechanism of Frost Action

The propagation of ice between the soil particles depends on pore size, that is, the smaller the pores and channels between pores, the lower is the temperature necessary before the ice front can advance. This provides means for supercooling the pore water beneath an actively growing ice lens. The subsequent release of energy in such a system creates a moisture suction gradient, which induces a moisture flow to the ice front and also develops a positive pressure to raise the overburden pressure and provide a space for the ice lens. Silt is the most favorable soil size for the frost heaving, since the particles are small enough to provide a comparatively high capillary rise, whereas the pores are large enough to allow a quick flow of moisture. Therefore silty soils are the most frost-susceptible soils.

Heaving Pressure

Heaving pressure is the pressure developed upon the freezing of soil when the soil is restrained from displacement. According to Burn (*5*) there is no apparent limit to the amount of heaving pressure that may occur upon the frost action in soil. However, the formation of ice lenses in a freezing soil can be arrested if the frost heaving pressure is counteracted by an equal or greater external pressure. Therefore, it is important in the design to be able to predict the magnitude of heaving pressure generated by the formation of ice lenses in soils upon freezing. Such pressure has been reported by Moore (*1*), who noticed a decrease in the horizontal dimension and an increase in the vertical dimension in few soil-steel structures.

Research on heaving pressures associated with the formation of ice lenses in soils indicates that the magnitude of the heaving pressure is governed by (*a*) the geometry of the ice-water interface, which involves a double curvature of ice front into the voids and around the adjacent particles (i.e., both particles and pore size distribution); and (*b*) the degree of restraint on the soil's displacements. Everett and Haynes (*6*) developed the following equation for calculating the heaving pressure:

$$dP = \frac{2\sigma_{iw}(1 + B)}{r} \qquad (1)$$

where

dP = heaving pressure,
σ_{iw} = interfacial energy between ice and water (20 ergs/cm^2),
r_{iw} = radius of curvature of meniscus passing through aperture in close-packed spheres,
r = the radius of the spheres (using the grain size analysis), and
$B = \frac{r}{r_{iw}}$ (experimentally determined, B = 5.6).

Penner (7) confirmed Equation 1 by measuring the pressure resulting from ice lens growth on pads of glass beads, unconsolidated material.

Heave pressure may overcome the restraint of the conduit, especially at the invert of pipe arches, were the soil pressure is low due to the large curvature of the conduit's invert. Also, the heave pressure could become considerably high if (*a*) the bedding soil is susceptible or changes with time to become susceptible to frost action, or (*b*) the depth of bedding is less than the frost penetration and is placed above native frost-susceptible soil.

To examine and qualitatively demonstrate the effect of heave pressure at the invert, a pipe arch is analyzed considering an upward pressure of 4 psi. This loading represents the excess of heave pressure over the pressure at the invert due to dead load. The analysis has been conducted by treating the conduit as a frame on elastic supports, representing soil with coefficients of reaction $k_n = E'/R$ in the direction perpendicular to the wall and $k_S = .2k_n$ in the tangential direction. In these equations E' is the modulus of soil reaction assumed at 6,000 psi and R is the local radius of curvature of the conduit wall (8). The analysis shows considerable bending moments developed at the invert and haunches when considering the effect of such uplift forces (see Figure 1b).

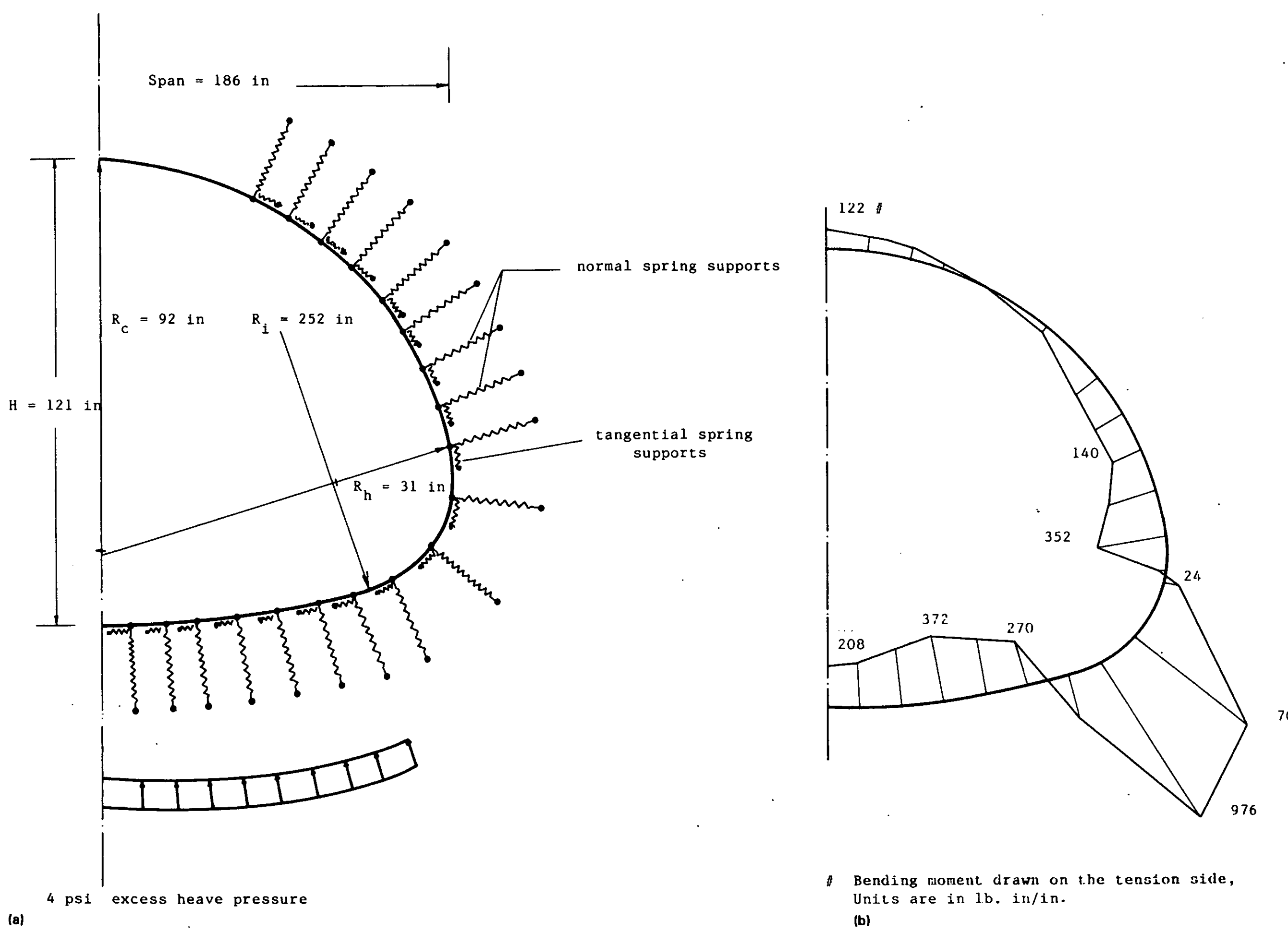

FIGURE 1 (*a*) Model for conduit analysis; (*b*) bending moment induced by heave pressure at the invert. Span D_H = 186 in.; rise = 121 in.; radius at crown R_c = 92 in., at invert R_i = 252 in., at haunch R_h = 31 in.; and heave pressure = 4 psi.

Depth of Frost Penetration

The depth of frost penetration is governed by the duration and degree of cooling of the air at the surface of the soil. This is usually expressed as the freezing index (FI), which is the cumulative total of degree-days of air temperature below freezing. A map showing the local FI has been published by Armstrong and Csathy (*9*).

An analytical formula has been developed by Stefan to calculate the depth of frost penetration (*10*). Also, a "design curve" has been developed experimentally by the U.S. Corps of Engineers showing a linear relation between the depth of frost penetration, d, and FI, which can be expressed as follows:

$$d = 0.0015(\text{FI}) \quad (2a)$$

where d is in meters and FI is in degrees-days Celsius, or

$$d = 0.035(\text{FI}) \quad (2b)$$

where d is in inches and FI is in degrees-days Fahrenheit.

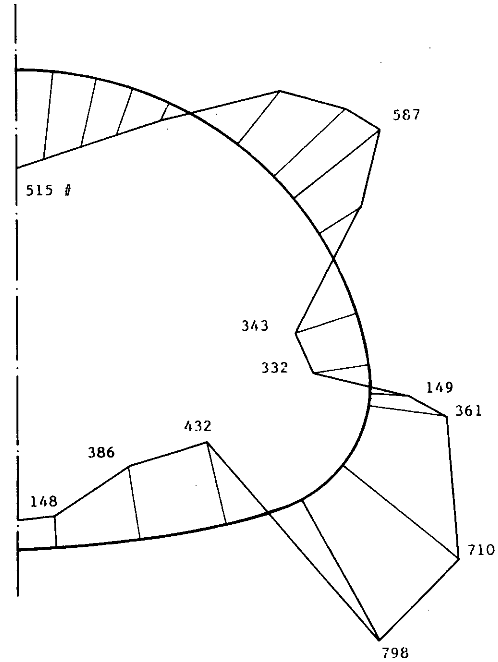

FIGURE 2 Bending moment induced by loss of soil support (stiffness) at the haunches. Spring supports at haunch reduced by 40 percent. Span D_H = 186 in.; rise = 121 in.; radius at crown R_c = 92 in., at invert R_i = 252 in., at haunch R_h = 31 in.

Thawing

Toward the end of winter or in early spring, upon thawing, the water released from the ice lenses causes local oversaturation until the excess water can be drained from the thawed zone. However, thawing commences from the inside surface of the conduit and progresses outward to the soil, while the nonthawed soil traps the excess water around the conduit. The increase of the water content of the soil causes a decrease in the soil density, and the induced high pore water pressure causes reduction of the shear strength of the soil. Therefore, loss of bearing capacity has been observed during thawing. The general behavior during a 1-year period has been reported by Jessenberger and Carbee (*11*), whose findings show that for soil tested under an arbitrary pressure of 0.83 psi, a reduction took place in the bearing capacity even for soil with 0, 2.0, or 6 percent of particles finer than 0.02 mm. Even for these so-called "frost nonsusceptible" soils, a reduction of 30 percent has been recorded, whereas reductions of 70 percent or more have been observed for frost-susceptible soil.

The loss of bearing capacity or the stiffness of the soil at the haunch is qualitatively demonstrated in Figure 2, which shows the bending moment induced in the conduit wall as a result of reduced stiffness of the soil at the haunches. Herein, the conduit outlined in Figure 1a is analyzed under dead load considering a loss of 40 percent of the force carried by the spring supports at the haunches. This leads to an increase in the bending moment in the conduit wall, especially in the vicinity of the haunch (Figure 2). This effect is similar to the effect of relaxation or consolidation of the soil behind the haunch.

A test has also been conducted to simulate the effect of ice melting (i.e., reduction in soil stiffness) behind the haunches. A model was built of corrugated aluminum plate with a thickness of 1 mm and depth of corrugation of 6 mm (see Figure 3). Six wooden rods were placed behind each of the haunches during construction. They were to be removed later, simulating loss of soil compaction (or stiffness) due to ice melting behind the haunches. Measurements were taken for strains and displacements of the model under loading at the embankment, before and after partial pulling of the rods. Details of these measurements are given by Abdel-Sayed and Ghobrial (*3*). Figure 4 shows the effects of loss of soil support at the haunches of the conduit. Herein, a load of 13 kN is applied through a rigid I beam and is considered to act uniformly over the length of the I beam (i.e., the width of the testing box). The induced deflection before pulling any of the dowels (i.e., before any loss of soil compaction behind the haunches) is shown by A, Figure 4. The deflection shape remained unchanged, whereas its magnitude increased considerably after pulling three, six, and nine dowels (Curves B, C, and D, respectively). This figure demonstrates the effect of frost action, which could lead to loss of consolidation of the soil behind the haunches. It shows that a small displacement at the haunch causes considerably magnified deflection at the crown as well as the corresponding bending moments.

IDENTIFICATION OF FROST-SUSCEPTIBLE SOILS

Frost action is a dynamic unsteady state process. Its nature is complex and involves a number of interrelated variables. It may be impossible to predict the exact effects of frost; however, the relative potential of frost to affect soil-steel

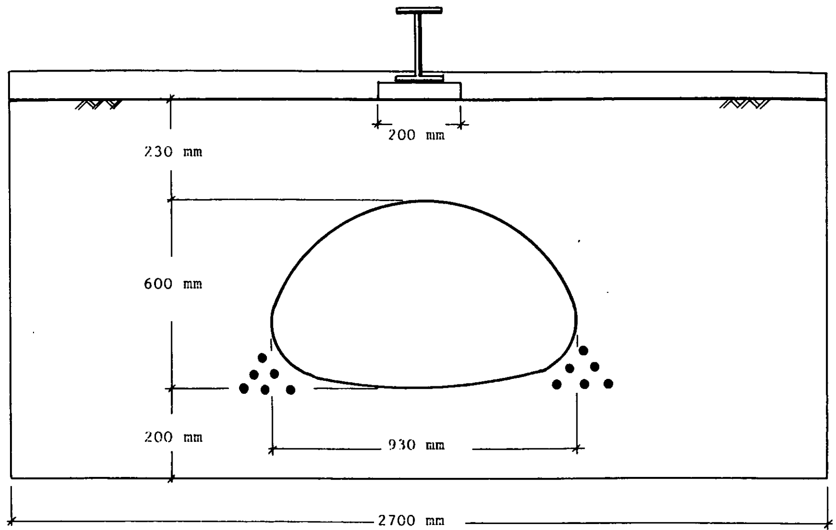

FIGURE 3 Model tested to simulate loss of soil support behind the haunches.

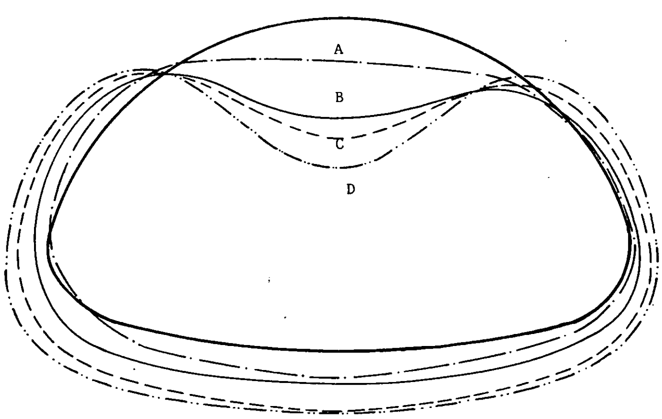

FIGURE 4 Deflection of model as related to loss of soil support behind the haunches. Deflection measured under a load of 13 kN: A, before pulling any dowels; B, after pulling three dowels from each side; C, after pulling five dowels from each side; and D, after pulling six dowels from each side.

structures could be estimated by studying the various factors that aid in its development.

Haley and Kapler (*12*) reported the results of tests that have been performed to determine the effects of individual factors considered to influence ice segregation in soils. Tests have been conducted on a large number of natural soils obtained from several locations and on specimens prepared by blending soil fractions in proportions to give desired investigational gradations. The test data show the following main characteristics:

1. The intensity of ice segregation in soils depends not only on the percentage of fine grains but also on the grain size distribution or physical-chemical properties of these fines.
2. In well-graded frost-susceptible gravelly soils, the intensity of ice segregation increases moderately with initial density up to approximately 95 percent of modified AASHO density, above which there is a decrease in ice segregation with increase in density.
3. The intensity of ice segregation in soils is decreased appreciably by an increase in overburden pressure, all other factors, such as rate of frost penetration, being equal.
4. The intensity of ice segregation in a frost-susceptible soil varies directly with the initial degree of saturation, where water is available only by withdrawal of a portion of that existing in the voids of the soil underlying the surface of freezing.

Whereas each of these criteria makes it possible to diagnose the frost susceptibility of a particular soil, it remains practically impossible to indicate the degree of frost susceptibility or its intensity.

Different frost criteria are used to identify and evaluate the frost susceptibility of soils. The most acknowledged definition is, according to Casagrande (*13*), "Under natural freezing conditions and with sufficient water supply (from ground water) one should expect considerable ice segregation in non-uniform soils containing more than 3% of grains smaller than 0.02 mm, and in very uniform soils containing more than 10% smaller than 0.02 mm."

FROST EFFECTS ON SOIL-STEEL STRUCTURES

The following is a numerical example to qualitatively illustrate the frost effects on a soil-steel structure. Herein, a pipe arch is considered with a span $S = 3.12$ m and height $H = 2.05$ m (Figure 5).

A depth of soil cover, $D = 1.2$ m, and a soil unit weight, $\gamma = 17.2$ kN/m, are assumed. According to the ring compression theory the soil pressures P at any point around the conduit are shown in Figure 5 as computed by the following equation:

$$P = \frac{\gamma DS}{2R} \qquad (3)$$

where R is the radius of curvature at the point under consideration. Herein, let us assume two kinds of soil backfill. Soil

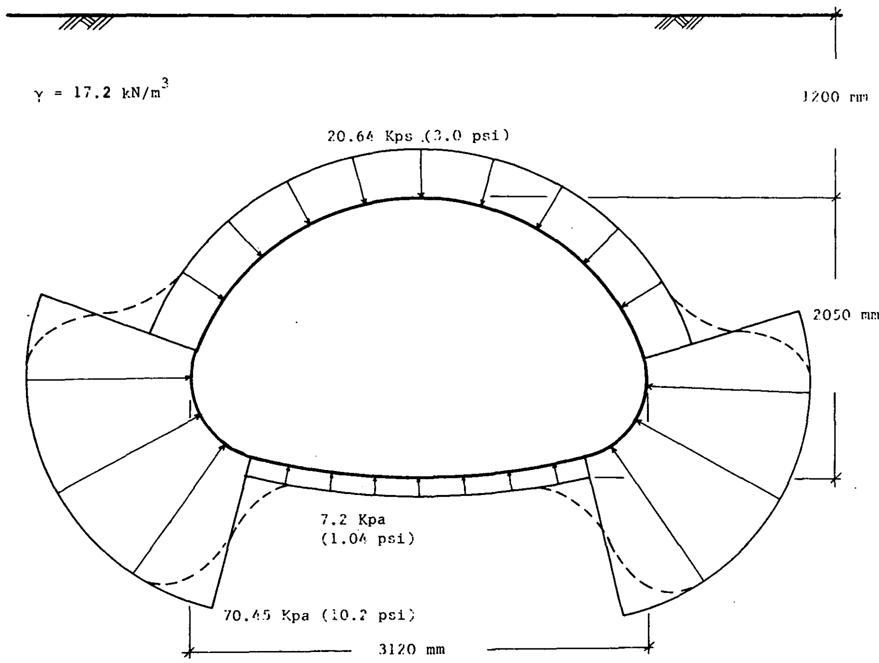

FIGURE 5 Example of a pipe arch showing earth pressure under dead load.

A is a well-graded soil with 3 percent by weight finer than 0.02 mm. According to the gradation characteristics, the effective diameter would be about 0.045 mm. Thus, a heaving pressure of 20 kPa (2.9 psi) is obtained from Equation 1. Soil B has 15 percent by weight finer than 0.02 mm and an effective diameter of 0.011 mm. Thus the heaving pressure is 84.0 kPa (12.15 psi). Therefore, the behavior at the invert and haunches can be analyzed as follows:

- Invert: It is assumed that the soil pressure shown in Figure 5 does not cause bending moment to the bottom plate. Yet, the soil pressure at the invert is 7.2 kPa (i.e., less than the heaving pressure of both Soils A and B). Therefore, the bottom plate will be subjected to bending moment during freezing period. Moreover, the soil underneath the conduit may heave toward the center of the conduit, uplifting the bottom plate in winter and causing oversaturation during thawing.
- Haunches: In the case of Soil A, the soil pressure at the corner plate is 70.45 kPa [i.e., larger than the heaving pressure (20 kPa)]. Therefore, it is expected that the ice lenses cease to grow, and the soil at the corner will not be subjected to frost action. However, at Point A″ just above the joint, this condition could be reversed, and an inward displacement may occur at this point.

In the case of Soil B the heaving pressure is 84 kPa, which is larger than the soil pressure at the corner plate. Therefore, the soil may heave toward the corner plate, causing moment and displacement in the corner plate and also providing more space for ice lenses to form.

Moreover, the ice lenses may grow in the direction of the native soil. This may cause displacement toward the native soil, which deforms permanently under pressure. Thus after thawing, the density and stiffness of the backfill will be reduced.

FROST SUSCEPTIBILITY OF SOIL-STEEL STRUCTURES

It is always recommended that clean granular soils be used for backfill. They are expected to be nonsusceptible to frost action. Also, the soil envelope is usually under pressure, which reduces its susceptibility to frost action. However, the frost effect should be examined in soil-steel structures because of the following:

1. Backfill material: According to the present AASHTO specification, the backfill soil should conform to one of the following soil classifications: "for heights of fill less than 3400 mm, A-1, A-3, A-2-4, and A-2-5, and for heights of fill of 3400 mm or more, A-1 and A-3." The code does not specify a limit for the percentage of the fine material. For example, Soil A-1 could have up to 25 percent silt and/or clay; also, Soils A-2-4 and A-2-5 could have up to 35 percent, which make them very frost susceptible and prone to the loss of bearing capacity, especially since frost susceptibility increases with the high degree of compaction that is usually performed around the culvert.

Moreover, the present OHBD code specifies two soil groups according to the grain size (coarse, medium, and fine) without limiting the percentage of the fine materials. For example, most of the soils in Group II have at least 12 percent silt and/or clay. If any of these soils were well graded, the percentage of the fine materials should not exceed 3 percent to avoid frost action problems.

Since the fine materials govern the frost susceptibility of the soil, their content must be specified in the codes. Casagrande's criterion is believed to be the most reliable one; it is followed for road construction by most state and provincial highway departments.

2. Depth of bedding: The present AASHTO specification and the OHBD code do not specify any thickness for the bedding or the backfill underneath the conduit. If the frost penetration depth is greater than the specified thickness of the backfill, the regular soil, which could be silty soil (frost susceptible), will freeze, forming ice lenses and high pressure on the conduit, and it may lose its supporting capacity during thawing. To avoid such troubles, the backfill material and the bedding soil must be non-frost-susceptible soil and must extend to at least the frost penetration depth.

Furthermore, granular soil placed for bedding and under the haunch may be subjected to water flow in two directions and to the possibility of infiltration of fine soil particles because of (*a*) water flow along the axis of the conduit, especially in the case of conduits with no end treatment (this could lead to considerable silt infiltration, especially in sand bedding near the inlet, and may explain the end uplift that was observed in a few conduits in Ontario), and (*b*) lateral water flow due to the freezing of fully saturated granular soil adjacent to the conduit wall and the reverse at thawing.

3. Soil material of the embankment: The present codes do not specify any soil group for the part of the embankment above the minimum depth of cover. However, the embankment material may affect the backfill material around the culvert. For example, the backfill around one of the culverts in Pennsylvania (*14*) had a low percentage of fine material, which made it non-frost-susceptible soil, but the embankment material above that culvert had about 57 percent clay and silt by weight. It is possible that these fine materials penetrate into the backfill around the culvert, changing it to frost-susceptible soil.

4. Construction technique: The present codes do not specify a certain compaction or construction technique to avoid the accumulation of fine materials in layers within the layered backfill. However, a thin layer of silt or clay could be accumulated during dumping and compaction of the backfill, which could be very detrimental. Beskow (*15*) stated, "In sands, if an ever so thin layer of fine material, silt, fine silt, or clay seam exists, an appreciable ice layer can form under favorable circumstances." Whereas the sand may appear at the surface to be non-frost-heaving soil, the existence of a thin layer of fine silt may make it strongly frost-heaving soil.

5. Poor construction practice: Some of the conduits may be built with "dirty" sand and gravel. It has been reported by Beskow (*15*) that adding a small amount of clay to the sand causes the mixture to become frost susceptible. He reported that 5 percent clay (corresponding to 2½ percent dry substance) causes a noticeable effect, 10 percent a considerable effect, and 20 percent very large effects. In the meantime bore tests in the backfill adjacent to pipe-arch bridges that are in distress (*14*) show the dominant character of the backfill to be "loose brown silty sand and gravel with occasional clayey silt lump." This leads to the unfortunate conclusion that many conduits have been or may be built with frost-susceptible soil.

RECOMMENDATIONS

As discussed, the durability of soil-steel structures can be enhanced by avoiding the frost effects as follows:

1. Non-frost-susceptible soil should be provided at the sides and invert of the conduit with a depth equal to or more than the frost penetration. This would require the delete of the listed silty sand or silty gravel soil which is allowed at the present in the OHBDC as well as the use of A-2-4 and A-2-4 from the AASHTO specifications. This may also require the excavation of native soil and its replacement with non-frost-susceptible granular soil under the invert.
2. Graded filter should be used or the embankment material should be selected such that no fine particles can be washed down and induce fine particle sedimentation in the backfill around the conduit.
3. Head walls should be provided, especially at the entrance of waterway conduits to avoid infiltration of fine particles under the invert.
4. Cement-modified soil may be used in the absence of non-frost-susceptible soil near the site of construction. Such treatment, in which 1 to 4 percent of portland cement is mixed with the soil, could change the soil characteristic and change it to non-frost-susceptible soil.

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